

An Inversion Technique to Derive Model Photospheres in Late-Type Stars from High-Resolution Spectroscopy: The Sun

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Abstract.

An inversion technique has been developed to recover LTE one-dimensional model photospheres for late-type stars from very high-resolution high signal-to-noise stellar line profiles. It is successfully applied to the Sun using a set of unblended Ti I, Ca I, Cr I and Fe I lines with accurate transition probabilities. Temperature stratification, continuum flux, centre-to-limb variation and wings of strong metal lines obtained from the resulting model are compared with those from other well-known theoretical and empirical solar models and show the reliability of the procedure.

1. The Inversion Code

A new version of the inversion code developed by Ruiz Cobo & del Toro Iniesta (1992) to derive model photospheres from solar Stokes profiles has been adapted to work with stellar flux line profiles as the only input. The program maximizes the agreement between the line spectrum emerging from the star and a synthetic spectrum, modeling the temperature stratification of the photosphere, the elemental chemical abundances, macroturbulence, microturbulence and the projected rotational velocity.

LTE and hydrostatic equilibrium constraints are imposed to the derived photospheric structure. Starting from a given model photosphere, step by step, the depth dependence of the temperature is allowed to be modified in a successively increasing number of nodes. Three snapshots in the inversion process are shown in Figure 1 (ordered a, b and c). The evolution of the goodness of the line profile fitting from an isothermal atmosphere to the final result can be easily understood from the accompanying animation.

The tests performed have pointed out the possibility of recovering the temperature in the photosphere from a few flux-calibrated line profiles, but showed how small errors in the absolute flux calibration translate in huge errors on the temperature scale. The possibility of recovering the LTE photospheric structure by using a larger number of locally normalized line profiles was also detected in the tests. This means a remarkable advantage, because that information can be available for any star, regardless of whether or not we know the distance to the star and the errors in the spectrophotometry become larger than for the solar case.

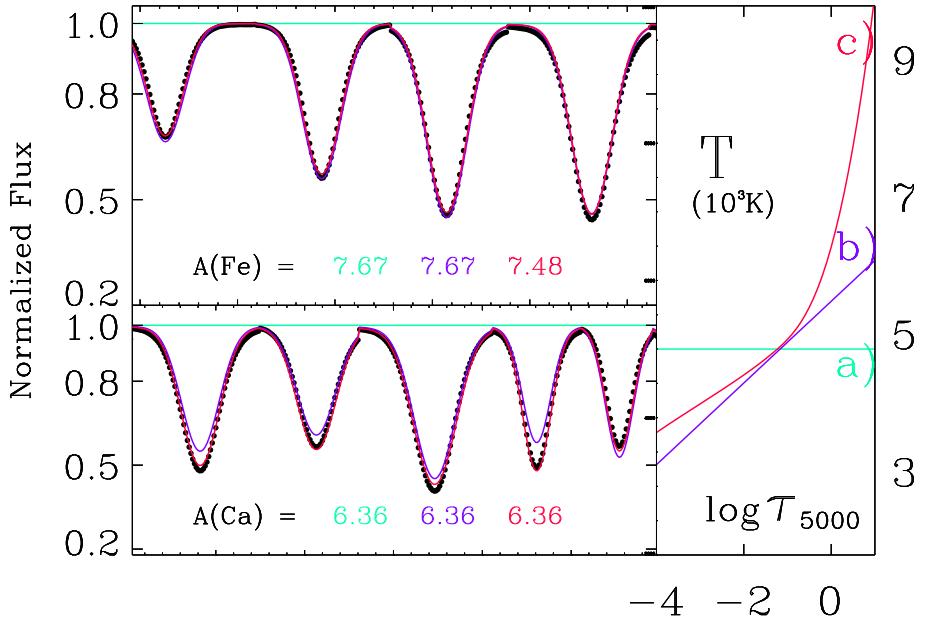


Figure 1. Three steps in the inversion procedure. From a constant temperature atmosphere, resulting in no spectral lines, to the final step where the line profiles are well reproduced. Nine of the 40 lines employed for the inversion are displayed.

2. It works for the Sun!

The method is applied to the Sun, the best known cool star, where direct comparison can be performed with other empirical and theoretical model photospheres.

The observations entering the inversion procedure are clean line profiles from the solar flux spectrum of Kurucz et al. (1984), which is available at the NOAO FTP site¹. The input lines to be included in the selection of solar lines by Meylan et al. (1993) were required, who identified clean line wings in the same atlas by fitting Voigt profiles. We also impose the condition for the line that its atomic transition probability had been measured at the Oxford furnace (e.g. Blackwell & Shallis 1979).

A total of 40 absorption lines of neutral iron, titanium, chromium and calcium were entered into the inversion program. The clean wings of the broad Ca I $\lambda 6162 \text{ \AA}$, one of the few lines for which the collisional width is accurately known, were also included.

The method is able to extract information about the photospheric region corresponding to the depth range where the employed lines are formed. The derived solar model photosphere is shown in Figure 2. Following the considerations by Meylan et al. (1993) to avoid blends, the whole line profile or just one wing was accepted as input data. Agreement is found when comparing its properties with observations and other well-known model photospheres:

¹<ftp://pandora.tuc.noao.edu/fts>

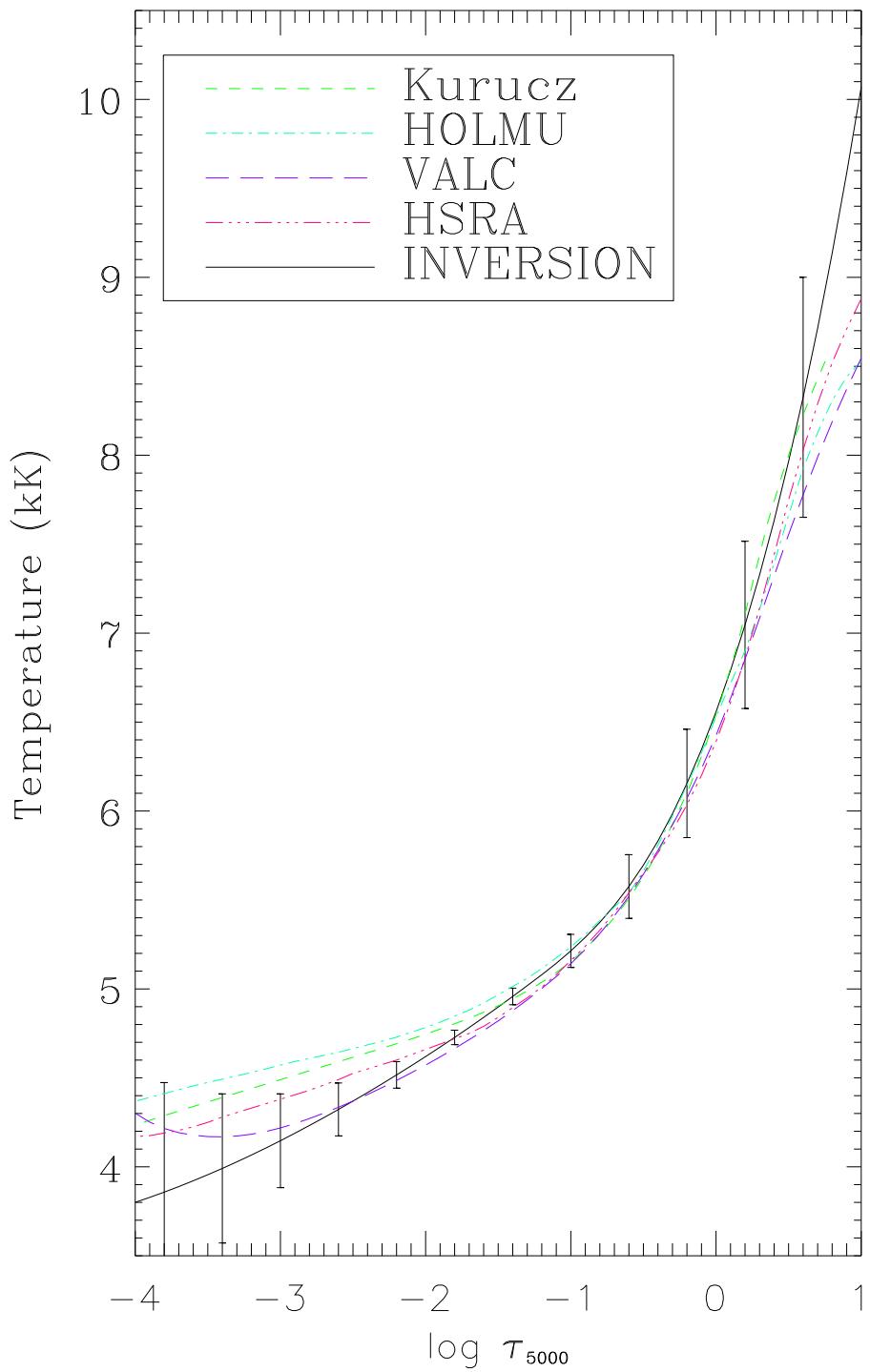


Figure 2. The photospheric temperature structure for the Sun obtained from the inversion method is directly compared with other classical models.

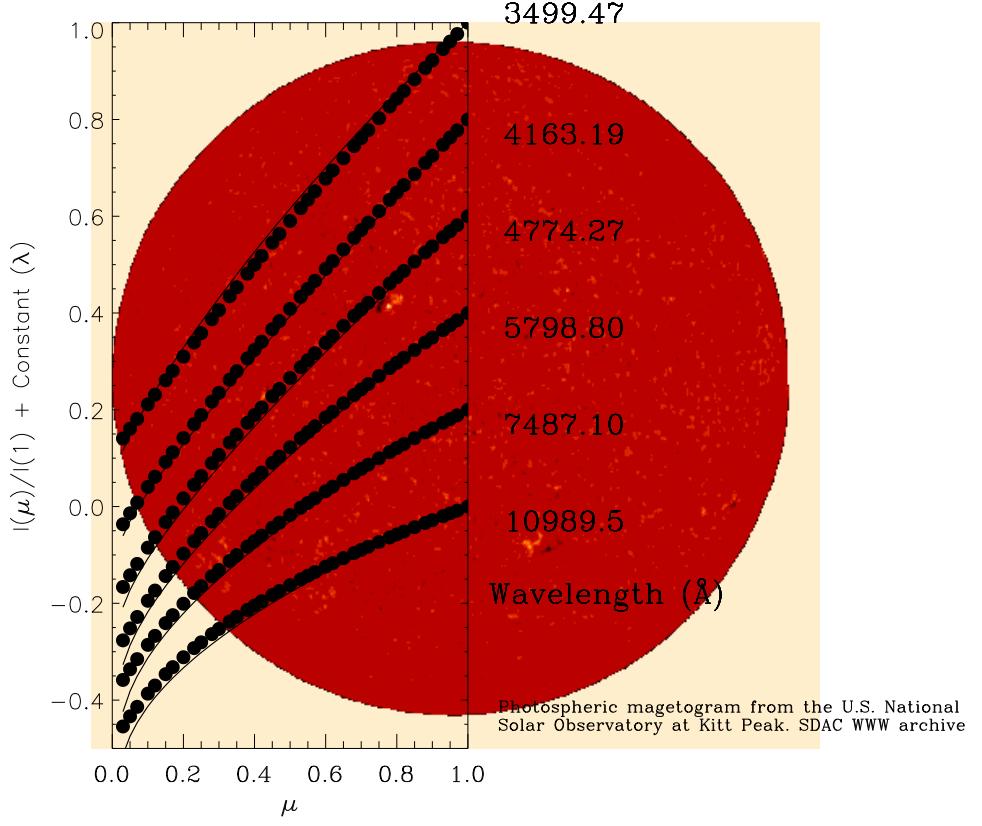


Figure 3. The predicted specific intensity, normalized to that at the disc-centre, is compared with the polynomial fits to the observations by Neckel & Labs (1994).

- Limb darkening. The continuum centre-to-limb variation predicted by the INVERSION model keeps close to the observations for the entire optical range (Figure 3).
- Continuum. Although the observed continuum cannot be easily translated to the true one, which limits its usefulness in the absolute calibration of the line profiles, it is possible to correct the wide-band observations, making use of high resolution spectra, to establish a lower limit to the true continuum. The pseudo-continuum deduced by Kurucz et al. (1984) from the data of Neckel & Labs (1984), is compatible with the predictions by HOLMU (Holweger & Müller 1974), Kurucz's model (Kurucz 1992) and the photosphere from the INVERSION.
- Wings of strong lines. We have also checked that the spectral range around Ca I λ 6162 Å is well reproduced by the model. Also, the predicted wings of the Sodium D doublet, which are supposed to cover a wide depth range of the photosphere, reproduce the solar measurements.

It is found that none of the input abundances (Anders & Grevesse 1989) for Cr, Ca, and Ti need to be changed to find the best fit of the observations, but the Fe abundance is preferred to vary from the initially assumed value (7.67, in a scale where the hydrogen abundance is 12) to the lower meteoric abundance 7.5.

Assuming the rotation velocity (1.88 km s^{-1}), and the microturbulence (0.6 km s^{-1}) as known, the code arrives at 1.7 km s^{-1} for the macroturbulent velocity.

3. Summary

From the inversion of NORMALIZED line profiles we derive a semi-empirical model photosphere for the Sun which reproduces the solar continuum, the limb-darkening in the continuum, and the profiles of lines which were not included in the input data for the inversion.

To better fit the solar flux line spectrum would require the rejection of the hypothesis of hydrostatic equilibrium, introducing multi-component models or velocity fields giving place to asymmetries in the line profiles. Work for the near future will point in this direction.

Making use of very high quality spectra (Allende Prieto et al. 1995) we plan to apply this tool to metal-poor stars and compare the results with LTE theoretical model atmospheres.

Acknowledgments. We sincerely thank Héctor Socas Navarro for carrying out some calculations for us. We are also grateful to Gabriel Pérez Díaz, who helped us with the movie work. NSO/Kitt Peak FTS data used here were produced by NSF/NOAO.

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